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Comparative study on three dynamic modulus of elasticity and static modulus of elasticity for Lodgepole pine lumber

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Abstract: The dynamic and static modulus of elasticity (MOE) between bluestained and non-bluestained lumber of Lodgepole pine were tested and analyzed by using three methods of Non-destructive testing (NDT), Portable Ultrasonic Non-destructive Digital Indicating Testing (Pundit), Metriguard and Fast Fourier Transform (FFT) and the normal bending method. Results showed that the dynamic and static MOE of bluestained wood were higher than those of non-bluestained wood. The significant differences in dynamic MOE and static MOE were found between bulestained and non-bluestained wood, of which, the difference in each of three dynamic MOE (E_p, the ultrasonic wave modulus of elasticity, E_m, the stress wave modulus of elasticity and E_f, the longitudinal wave modulus of elasticity) between bulestained and non-bluestained wood arrived at the 0.01 significance level, whereas that in the static MOE at the 0.05 significance level. The differences in MOE between bulestained and non-bluestained wood were induced by the variation between sapwood and heartwood and the different densities of bulestained and non-bluestained wood. The correlation between dynamic MOE and static MOE was statistically significant at the 0.01 significance level. Although the dynamic MOE values of E_p, E_m, E_f were significantly different, there exists a close relationship between them (arriving at the 0.01 correlation level). Comparative analysis among the three techniques indicated that the accurateness of FFT was higher than that of Pundit and Metriguard. Effect of tree knots on MOE was also investigated. Result showed that the dynamic and static MOE gradually decreased with the increase of knot number, indicating that knot number had significant effect on MOE value.

Keywords: Lodgepole pine; Non-destructive testing; Dynamic modulus of elasticity; Static modulus of elasticity

Introduction

Non-destructive testing (NDT) is an effective method for quickly testing and evaluating the properties of materials, which does not destroy the physical, chemical, mechanical properties of materials and has no influence on future performance. The exploitation and application of this technology have been quickly developed in wood and wood-based panel fields for its evident advantages.

The modulus of elasticity (MOE), one of primary indexes in evaluating mechanical properties of wood, indicates the degree of wood resisting distortion. A higher value of MOE indicates that the material is not easy to be distorted and has a high rigidity., Many studies on testing and evaluating the wood MOE by NDT technology have been conducted in developed countries, and researchers' efforts have paved the way for successful application of NDT to various materials such as standing trees, lumbers, logs and wood-based panels and so forth (Wang *et al*. 2001; Ayarkwa *et al*. 2001; Ross *et al*. 2005; Najafi *et al*. 2005)., Although the research on application of NDT in wood field started later in China compared to the developed countries, in recent ten years, NDT has also been widely used in testing of lumber, veneer, fiber board and particleboard, etc. in China, and the study concerning NDT has being extended from original basic theories to online testing (Liu *et al*. 2005; Hu *et al*. 2001a, b; Cui *et al*. 2005).

The primary objective of this study is to investigate the dynamic MOE of lumber obtained from bulestaine and non-bulestained wood of Lodgepole pine by three NDT methods, Portable Ultrasonic Non-destructive Digital Indicating Testing (Pundit), Metriguard, and Fast Fourier Transform (FFT). In the present study, the difference and relationship between dynamic MOE and static MOE were analyzed and the accurateness and reliability of MOE evaluated by the three NDT techniques were discussed. The findings of this study can provide scientific references for quickly testing wood and selecting appropriate means of NDT.

Materials and methods

Materials

The specimens selected were lumbers of Lodgepole pine from the British Columbia, Canada. The lumbers were divided into two groups, bulestained wood and non-bulestained wood. After cutting timbers, the lumbers were stored at room for air-dry, and then the lumber with no crack were selected to process the test samples. The density, moisture content, length, width and thickness of testing samples were measured. The basic situation of the test samples was presented in Table 1.

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Table 1. The basic situation of the test samples

Type	Number	Density ($g\cdot cm^{-3}$)	Moisture (%)	Length (mm)	Width (mm)	Thickness (mm)
Bluestained wood	60	0.531	8.14	500	65	17
Non-bulestained wood	60	0.502	8.16	500	65	17

Testing of the dynamic modulus of elasticity

Metriguard

Metriguard, a stress wave timer, is developed on the basis of the relationship among propagation time of longitudinal stress wave, material density and MOE. Test theory: Instrument was fixed at the highest level for the purpose of being unaffected by background vibration and maximizing sensitivity. Transducers were clamped to each beam's pith-side tangential face at constant pressure. When a pendulum exerted on the clamp, a longitudinal stress wave in each beam of one inch was induced and formed the “start” transducer. Stress wave propagate in materials and propagation time was measured, then the velocity of stress wave was calculated. The stress wave modulus was calculated by using the following equation.

$$E_m = \frac{c^2 p}{g} \tag{1}$$

where, $\boldsymbol{E_m}$ is the stress wave modulus of elasticity (GPa), c the velocity of stress wave ($m\cdot s^{-1}$), ρ the material density ($kg\cdot m^{-3}$), and g the acceleration due to gravity ($m\cdot s^{-2}$).

Pundit

Pundit is an ultrasonic testing instrument. Test theory: Two transducers were fixed on each side of wood sample. The start transducer excitated ultrasonic transmit in wood sample. Transmission time of ultrasonic was measured by receive transducer, and velocity of sound wave was calculated. The dynamic MOE was evaluated through the relationship between sound wave velocity, specimen density and ultrasonic modulus of elasticity. The ultrasonic wave modulus of elasticity (GPa) was calculated by the following equation.

$$E_p = c^2\rho \tag{2}$$

where, $\boldsymbol{E_p}$ is the ultrasonic wave modulus of elasticity (GPa), c the velocity of ultrasonic wave ($m\cdot s^{-1}$), and ρ the material density ($kg\cdot m^{-3}$).

FFT

FFT technique mainly applies computer technology to analyze quickly signal frequency. Test theory: Bending vibration was induced by a hammer impacting the samples and the attenuate sound wave was collected by microphone placed on the side of specimen. Resonance frequency was measured by FFT and calculated on the basis of the instant frequency analysis. Longitudinal wave dynamic MOE was calculated by using the following equation.

$$E_f = 4L^2 f^2\rho \tag{3}$$

where, $\boldsymbol{E_f}$ is the longitudinal wave modulus of elasticity (GPa), L the material length (mm), f the natural frequency of transversely vibrating material (Hz), and ρ the material density ($kg\cdot m^{-3}$).

Testing of the static modulus of elasticity

The static MOE (*Es*) was performed primarily by mechanic testing machine (Japan, AH-50KNB), based on China standard (GB1936.2-91 1991). The experiment was adjusted properly by using four-point loading test according to China standard. The maximum values of loading and speed designed in the experiment was 800 N and 2 mm/min for preventing excessive distortion.

Results and analysis

Comparative analysis of bulestained and non-bluestained wood

Three dynamic MOE values and static MOE values of bulestained wood and non-bulestained wood were measured by the above three testing methods. Test results were shown in Table 2. The values of E_p, E_m, E_f and Es of bulestained wood (ρ = 0.531 $g\cdot cm^{-3}$) were higher than those of non-bulestained wood (ρ = 0.502 $g\cdot cm^{-3}$). The differences of the above parameters between the two kinds of wood were 0.8 GPa (E_p), 0.96 GPa (E_m), 1.32 GPa (E_f) and 0.68 GPa (Es).

Table 2. The dynamic and static modulus of elasticity between bluestained and non-bluestained wood

Type	E_p			E_m			E_f			E_s		
	Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)
Bluestained wood	15.54	1.92	12.38	14.12	1.59	11.25	13.97	2.11	15.14	12.07	1.42	11.77
Non- Bluestained wood	14.54	1.93	13.26	13.16	1.81	13.76	12.65	1.97	15.61	11.39	1.65	14.46
Mean	15.04	1.98	13.18	13.64	1.76	12.93	13.31	2.14	16.7	11.73	1.57	13.78

Note: S is the standard deviation, CV the variation coefficient, E_p the ultrasonic wave modulus of elasticity, E_m the stress wave modulus of elasticity, E_f the longitudinal wave modulus of elasticity, E_s the static modulus of elasticity

The statistic analysis between bulestained and non-bulestained wood showed that the F-values of E_p, E_m, E_f and Es were 8.113, 9.615, 12.464 and 5.891, respectively. The results indicated the significant difference in three dynamic MOE and static MOE between bulestained and non-bluestained wood. The difference in each of three dynamic MOE between bulestained and

non-bluestained wood arrived at the 0.01 significance level ($F_{0.01}$ (1, 118) = 6.857) and that in static MOE arrived at the 0.05 significance level ($F_{0.05}$ (1, 118) = 3.921). A previous study (Byrne and Uzunovic 2000) showed that the difference in MOE was not significant between bulestained and non-bulestained wood of Lodgepole pine. One reasonable explanation for our findings is that the difference in MOE between bulestained and non-bluestained wood was mainly caused by the properties of sapwood and heartwood, because the bulestained wood mostly consisted of sapwood and the non-bulestained wood consisted of heartwood. The other possible explanation is that the density of bulestained wood was higher than that of non-buliestained wood, which may lead to the significant difference in MOE between bulestained wood and non-buliestained wood.

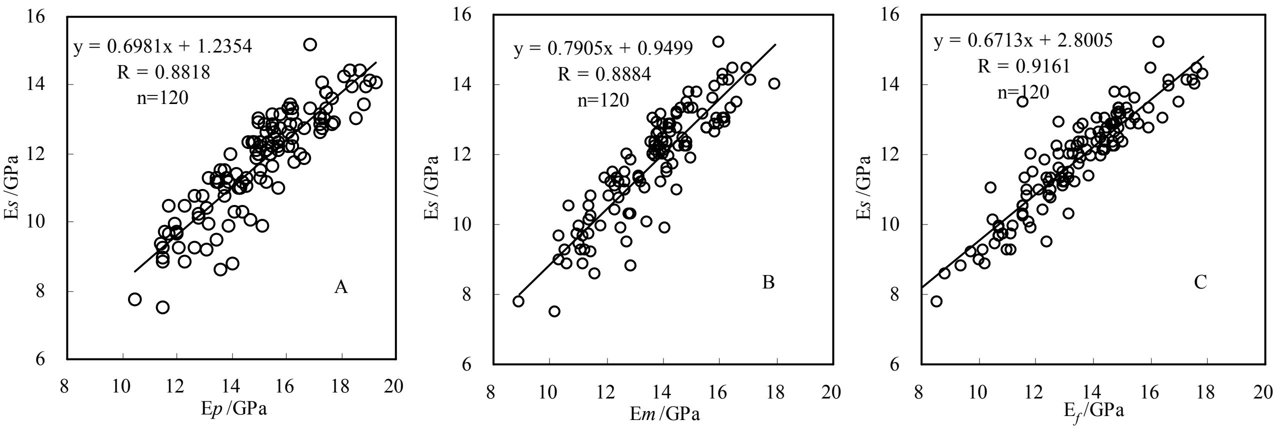

Fig. 1 The correlation between three dynamic modulus of elasticity and static of modulus of elasticity.
E_p represents the ultrasonic wave modulus of elasticity, E_m the stress wave modulus of elasticity, E_f the longitudinal wave modulus of elasticity, E_s the static modulus of elasticity

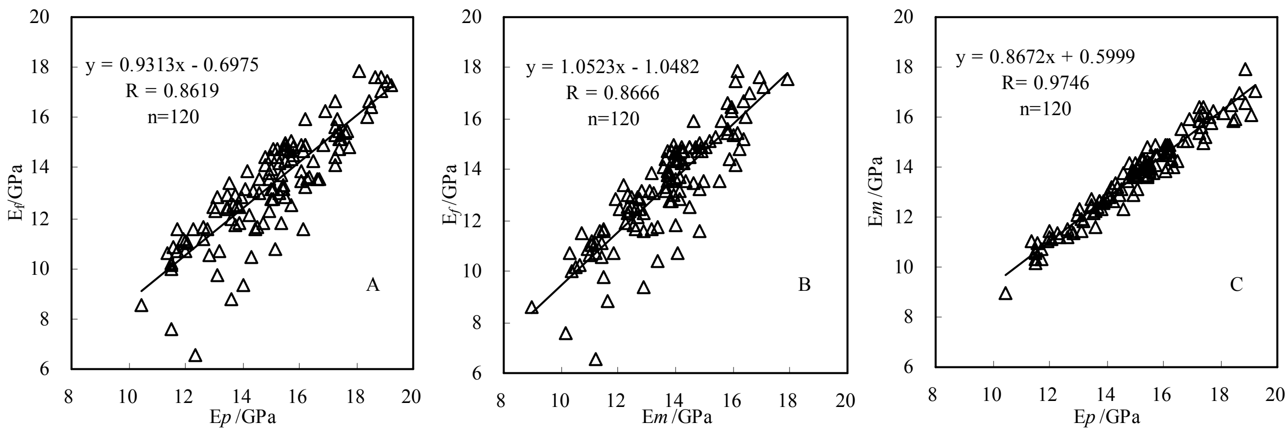

Fig. 2 The correlation among three dynamic modulus of elasticity
E_p represents stands for the ultrasonic wave modulus of elasticity, E_m the stress wave modulus of elasticity, E_f the longitudinal wave modulus of elasticity

Analysis of relationship between dynamic MOE and static MOE

All samples of bulestained wood and non-bluestained wood were combined as a collectivity to analyze the relationship between dynamic MOE and static MOE. As shown in Fig. 1 A-C, correlation coefficients were 0.8818 between $\boldsymbol{E_p}$ and $\boldsymbol{E_s}$, and 0.8884 between $\boldsymbol{E_m}$ and $\boldsymbol{E_s}$ both at the 0.01 significance level, and the maximum correlation coefficient occurred between $\boldsymbol{E_f}$ and $\boldsymbol{E_s}$, arriving at 0.9161. The correlation analysis demonstrated that Pundit, Metriguard and FFT were feasible to predict MOE, and FFT technique had a higher precision degree than Pundit and Metriguard for the prediction, as indicated by the maximum R value between E_f and E_s.

Comparative analysis of three dynamic MOE

The average values of E_p, E_m, E_f were 15.04 GPa, 13.64 GPa and 13.31 GPa, respectively (Table 2). The sequence of the three dynamic MOE from high to low was $E_p > E_m > E_f$. The results indicated that the dynamic MOE obtained from FFT technique was closer to the static MOE (11.73 GPa), and also validated the higher precision degree of FFT technique than Pundit and Metriguard.

Comparative analysis of the relationship among three dynamic MOE was presented in Fig. 2 A-C. Correlation coefficient was

0.8619 for E_f and E_p , 0.8666 for E_f and E_m (both at the 0.01 significance level), and 0.9746 for E_p and E_m. The testing means of Pundit and Metriguard were both based on the relationship among transmission speed, material density and MOE. Although the wave sources of Pundit and Metriguard were induced by different ways, they had similar wave type, transmission principle and testing manner.

Although the dynamic MOE values of E_p, E_m, E_f were significantly different, which is mainly caused by the anisotropy of wood material and the difference in testing principles, there exists a close relationship between the three methods of non-destructive testing.

Effect of tree knots on MOE

All the test samples were sorted according to knot number and the values of dynamic MOE and static MOE were calculated to analyze the effect of knots on MOE. Table 3 showed the results of sorting and calculation. The average values of E_p, E_m, E_f and Es of samples without knot were 2.07%, 3.23%, 10.27% and 7.47%, respectively, higher than those of the samples with knot.

Table 3. The dynamic and static modulus of elasticity of different tree knots

Type	Samples number	Knot number	E_p			E_m			E_f			E_s		
			Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)	Mean (GPa)	S (GPa)	CV (%)
No knot	50	0	15.22	2.06	13.5	13.9	1.71	12.3	14.07	1.89	13.45	12.23	1.36	11.16
	51	1	15.07	2.06	13.67	13.59	1.91	14.06	13.04	2.27	17.39	11.55	1.68	14.53
Knot	19	2	14.47	1.51	10.43	13.1	1.4	10.72	12.01	1.65	13.69	10.92	1.38	12.69
	70	Mean	14.91	1.93	12.97	13.46	1.79	13.31	12.76	2.15	16.89	11.38	1.62	14.23

Note: S is the standard deviation, CV the variation coefficient, E_p the ultrasonic wave modulus of elasticity, E_m the stress wave modulus of elasticity, E_f the longitudinal wave modulus of elasticity, E_s the static modulus of elasticity

Three dynamic MOE values and static MOE value gradually decreased with the increase in tree knot number (Fig. 3). It indicated that knot number had significant effect on MOE. However, the effects were quite complex, and possibly contributed by many factors such as the number of tree knots, the size of materials, conjoint degree between knots and around wood as well as stress distribution near the knots.

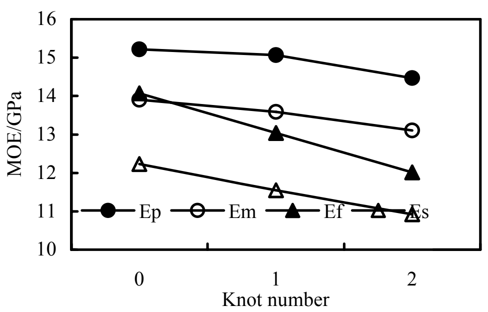

Fig. 3 The effect of knot number on modulus of elasticity

Conclusion

The dynamic and static MOE values of bulestained wood were higher than those of non-bulestained wood in this study. Statistic analysis indicated the significant difference in three dynamic MOE and static MOE between bulestained wood and non-bluestained wood. The difference among three dynamic MOE was at the 0.01 significance level and the static MOE at the 0.05 significance level. The above differences were mainly induced by the different properties between sapwood and heartwood. The E_p, E_m, E_f and Es have close relationship one another, all arriving at the 0.01 correlation level, and the most significant correlation (R = 0.9161) was found between E_f and Es. Through analyzing the relationship between three dynamic MOE and static MOE and comparing among three dynamic MOE, the precision degree of FFT technique was significantly higher than that of Pundit and Metriguard. The knot number had significant effect on MOE value, namely, the dynamic MOE and static MOE gradually decreased with the increase in tree knots number.

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